

Late Holocene Eolian Activity in the Mineralogically Mature Nebraska Sand Hills

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The age of sand dunes in the Nebraska Sand Hills has been controversial, with some investigators suggesting a full-glacial age and others suggesting that they were last active in the late Holocene. New accelerator mass spectrometry radiocarbon ages of unaltered bison bones and organic-rich sediments suggest that eolian sand deposition occurred at least twice in the past 3000 ^{14}C yr B.P. in three widely separated localities and as many as three times in the past 800 ^{14}C yr at three other localities. These late Holocene episodes of eolian activity are probably the result of droughts more intense than the 1930s "Dust Bowl" period, based on independent Great Plains climate records from lake sediments and tree rings. However, new geochemical data indicate that the Nebraska Sand Hills are mineralogically mature. Eolian sands in Nebraska have lower K-feldspar (and K_2O , Rb, and Ba) contents than most possible source sediments and lower K-feldspar contents than dunes of similar age in Colorado. The most likely explanation for mineralogical maturity is reduction of sand-sized K-feldspar to silt-sized particles via ballistic impacts due to strong winds over many cycles of eolian activity. Therefore, dunes of the Nebraska Sand Hills must have had a long history, probably extending over more than one glacial–interglacial cycle, and the potential for reactivation is high, with or without a future greenhouse warming.

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INTRODUCTION

Extensive tracts of unconsolidated, stabilized dunes and sand sheets are found on the semiarid to subhumid Great

Plains of North America. The 50,000 km^2 Nebraska Sand Hills area is the largest dune field (active or stabilized) in the western hemisphere (Fig. 1). We report here new studies of Nebraska Sand Hills eolian history based on stratigraphy and accelerator mass spectrometry (AMS) ^{14}C dating of enclosed bison bones and underlying organic-rich alluvium. We also report mineralogical and geochemical studies of Sand Hills sediments that have implications for the long-term history of this sand sea.

A wide variety of stabilized eolian landforms are found in the Nebraska Sand Hills (Smith, 1965; Ahlbrandt and Fryberger, 1980; Swinehart, 1990). Barchanoid-ridge dunes are as much as 50 km long and are visible on Landsat imagery (Fig. 2). Barchans, linear dunes, parabolic dunes, dome-like dunes, and sand sheets are also all found in the Nebraska Sand Hills. Measurement of slipfaces of stabilized dunes and dip azimuths of high-angle foreset beds indicate that paleowinds originated from the northwest and north, similar to modern wind regimes (Warren, 1976; Ahlbrandt and Fryberger, 1980). Smaller dune fields are found in southwestern Nebraska and adjacent north-eastern Colorado (Fig. 1), where the main eolian landforms are simple and compound parabolic dunes and older sand sheets (Madole, 1995; Muhs *et al.*, 1996a).

Several investigators assert, or assume, that dunes in the Nebraska Sand Hills were last active on a large scale during the full-glacial period about 22,000–16,000 yr B.P. (Watts and Wright, 1966; Warren, 1976; Sarnthein, 1978; Wells, 1983; Kutzbach and Wright, 1985). In contrast, other investi-

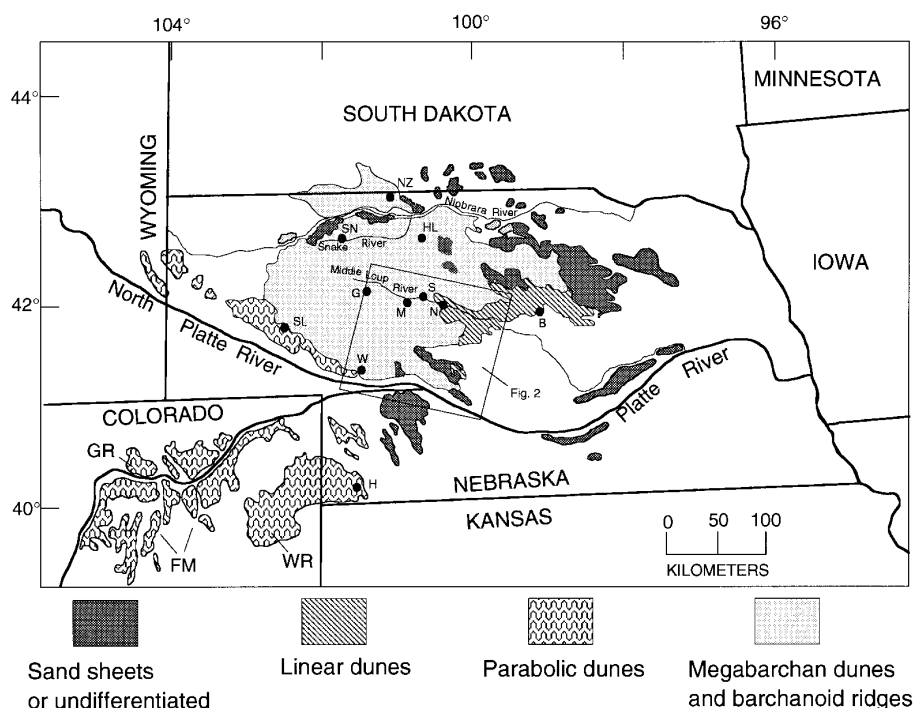


FIG. 1. Map showing distribution of eolian sand and bedform types in Nebraska, Colorado, and portions of adjacent states, and radiocarbon localities. Eolian sand distribution and bedform types compiled from Swinehart (1990), Swinehart *et al.* (1994), and Muhs *et al.* (1996a). Localities mentioned in text: GR, Greeley dune field; FM, Fort Morgan dune field; WR, Wray dune field; SN, Snake River; S, Seneca; M, Quarry near Mullen; N, Natick; W, Whitetail Creek; H, Hoover blowout; G, Gudmundsen; NZ, Nenzel; B, Burwell; SL, Swan Lake; HL, Hackberry Lake.

gators present ^{14}C data supporting several periods of dune movement within the past 8000 yr (Ahlbrandt *et al.*, 1983; Swinehart and Diffendal, 1990; Loope *et al.*, 1995). A Holocene age for the most recent episodes of dune movement agrees with studies of dune fields elsewhere in the Great Plains, such as Texas and New Mexico (Holliday, 1995, 1996), Kansas (Arbogast, 1996), Colorado (Madole, 1995; Forman *et al.*, 1995; Muhs *et al.*, 1996a), North Dakota (Running and Boughton, 1996; Muhs *et al.*, 1996b), Saskatchewan (Wolfe *et al.*, 1995), and Manitoba (David, 1971a). In an intermediate position, Smith (1965) and Wright *et al.* (1985) hypothesized that the principal dune forms in the Nebraska Sand Hills are Pleistocene, but there may have been intensive Holocene reactivation in some areas. Recently, Loope *et al.* (1995) and Mason *et al.* (1997) conclude that eolian sand blocked drainages within the Sand Hills during both the late Pleistocene and the middle Holocene.

The timing of past eolian deposition is important for predicting the degree of activity in the future. Dunes in most parts of the Great Plains, including the Nebraska Sand Hills, are presently inactive and stabilized by prairie vegetation. If the dunes are primarily an ice-age relic, then reactivation in the near future is unlikely. On the other hand, if the dunes were active during the Holocene, then future climatic conditions, whether due to natural variability or to human causes (such as greenhouse warming), may bring about re-

newed eolian activity. Higher temperatures, combined with significant reductions in precipitation, would reduce vegetation cover and could therefore bring about reactivation of many currently stabilized dunes (Muhs and Maat, 1993).

METHODS

In the Nebraska Sand Hills, we found bones of bison and smaller, unidentified mammals. These bones either underlie eolian sands or occur in paleosols within eolian sands. Skeletal elements were identified taxonomically as *Bison* spp. Bison bones are ideal for ^{14}C dating because they are taxonomically distinct and large enough to preclude most vertical postdepositional movement. The accuracy of bone ^{14}C ages is very high because (1) simultaneous advancements in AMS physics and bone dating chemistry (Stafford *et al.*, 1987, 1991) provide protocols for obtaining accurate bone collagen ages, (2) the bison bones dated in this study were physically and chemically very well preserved, based on C, N, and amino acid concentrations (Table 1), and (3) two drastically different chemical fractions were analyzed (Stafford *et al.*, 1987), thus allowing cross-checks on whether the bones experienced closed-system conditions with respect to carbon. Organic-rich alluvium (humic acid fraction) was also dated at two localities; details of the extraction methods are outlined in Abbott and Stafford (1996). Stable carbon and nitro-

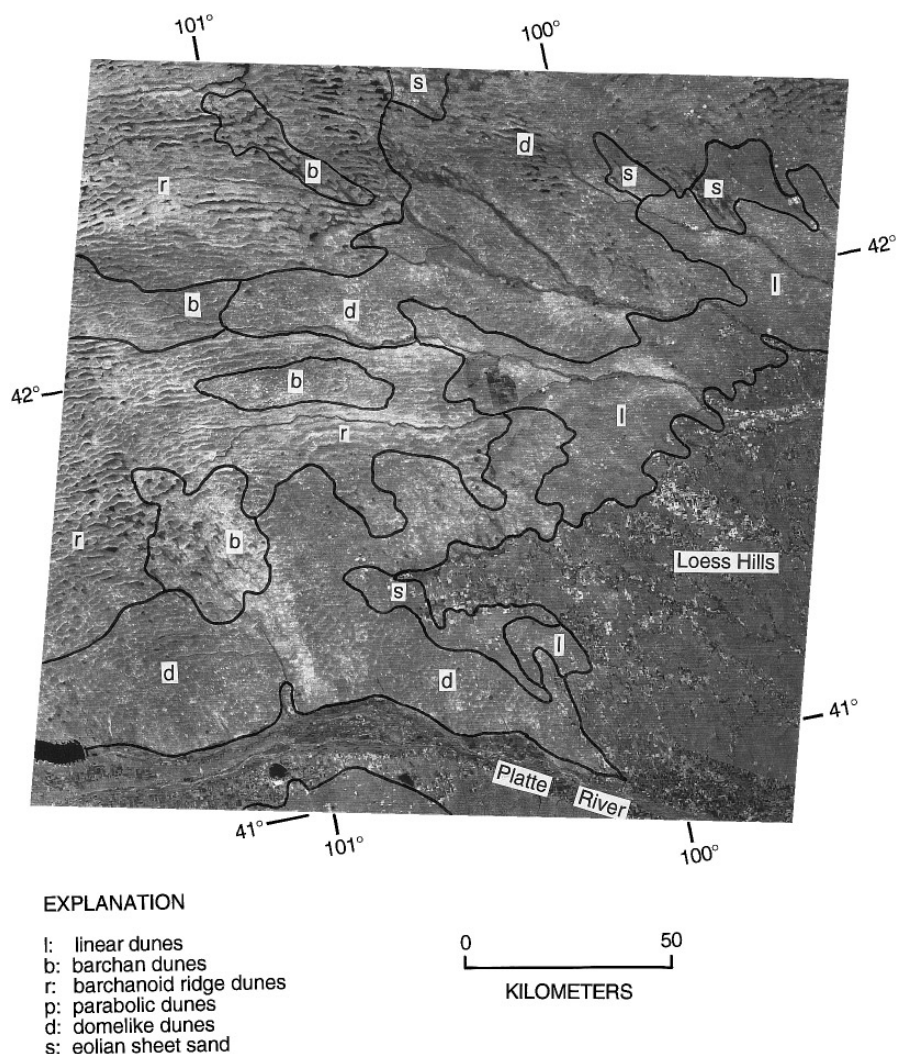


FIG. 2. Landsat MSS 5 image of the central and eastern portion of the Nebraska Sand Hills, showing various types of eolian bedforms. Eolian bedform types from Swinehart *et al.* (1994).

gen isotopic compositions of the bones were determined by mass spectrometry; previous studies have shown that the C and N isotopic composition of bone reflects the isotopic composition of the plants comprising the animal's diet (Hare *et al.*, 1991). Mineralogical and geochemical studies of the Nebraska dune sands and possible source sediments were conducted using X-ray diffraction and energy-dispersive X-ray fluorescence methods following those outlined by Muhs *et al.* (1995, 1996a).

STRATIGRAPHY AND RADIOCARBON AGES

Eolian Sand Deposition in the Past 3000 yr

New evidence was found of eolian sand deposition in the past 3000 yr at three widely separated localities in the Nebraska Sand Hills. In the southwestern Sand Hills, headward

erosion by Whitetail Creek, northeast of Ogallala, has exposed sediments in an area of dome-like dunes that have been re-worked into parabolic dunes (Fig. 1). Field relations suggest that the present channel of Whitetail Creek postdates some of these parabolic dunes. We studied exposures in this area that had previously been described by Ahlbrandt *et al.* (1983) and May *et al.* (1995). On both sides of Whitetail Creek, 5–6 m of eolian sand are underlain by 2–3 m of paludal (?) sandy silts which are in turn underlain by up to 20 m of Pliocene sand sheet deposits (Fig. 3). Radiocarbon ages of bison bone from both sides of Whitetail Creek support the interpretation that eolian sedimentation began sometime between ~2900 and ~2000 ^{14}C yr B.P. Eolian sedimentation was still in progress at ~2000 ^{14}C yr B.P. Both sections contain buried soils above the dated bones that have weak, A/AC/C profiles, indicating two periods of eolian deposition.

TABLE 1
Analytical Data for Fossil Bones from Nebraska

LLNL no. ^a	INSTAAR no. ^b	Loc.	C (%)	N (%)	AA/bone ^c (nm/mg)	Fraction ^d	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	Fm ^e	Error	¹⁴ C age (yr B.P.)	Cal. age (2 σ) ^f (yr B.P.)
CAMS-3496	NSRL-407	Hoover	12.23	3.97	1536	Coll.	-11.7	+5.1	0.9564	0.0067	360 ± 60	515–290
CAMS-5301	NSRL-407					Carb.	-6.7		0.9446	0.0068	290 ± 60	491–0
CAMS-3491	NSRL-406	Seneca central, upper soil	11.89	3.89	1766	Coll.	-15.7	+3.4	0.9730	0.0103	220 ± 60	478–0
CAMS-5302	NSRL-406					Carb.	-8.3		0.9727	0.0068	220 ± 90	478–0
CAMS-3497	NSRL-408	Seneca central, lower soil	8.58	2.61	652	Coll.	-12.5	+3.3	0.9090	0.0079	770 ± 70	788–564
CAMS-5303	NSRL-408					Carb.	-5.1		0.9450	0.0095	450 ± 90	640–299
CAMS-3494	NSRL-411	Seneca east	7.62	2.24	954	Coll.	-13.1	+5.3	0.9715	0.0072	230 ± 60	435–0
CAMS-5309	NSRL-411					Carb.	-5.7		0.9704	0.0094	240 ± 80	479–0
CAMS-3495	NSRL-443	Mullen quarry	8.05	2.79	770	Coll.	-7.3	+4.0	0.9343	0.0099	550 ± 90	665–339
CAMS-5310	NSRL-443					Carb.	-0.1		0.9285	0.0066	600 ± 60	663–514
CAMS-3492	NSRL-409	White-tail Creek, west	3.54	0.74	205	Coll.	-9.8	+3.9	0.7735	0.0054	2060 ± 60	2146–1874
CAMS-5306	NSRL-409					Carb.	-2.4		0.7471	0.0053	2340 ± 60	2701–2157
CAMS-3493	NSRL-410	White-tail Creek, east	3.45	0.28	111	Coll.	-9.0	+3.7	0.7390	0.0075	2430 ± 90	2749–2213
CAMS-5311	NSRL-410					Carb.	-1.6		0.7002	0.0050	2860 ± 60	3202–2797

^a Lawrence Livermore National Laboratory number.

^b Institute of Arctic and Alpine Research (University of Colorado) laboratory number.

^c Total amino acid concentration per unit of bone.

^d Coll., purified collagen; Carb., carboxyl CO₂ fraction.

^e Fm, fraction of modern ¹⁴C content.

^f Calendar age (calibrated from Stuiver and Pearson, 1993; Pearson and Stuiver, 1993).

Much of the northwestern and central part of the Sand Hills is characterized by complex megabarchan and barchanoid-ridge dunes (Swinehart, 1990). East-west-trending barchanoid-ridge dunes are 20–40 km long and correspond to Smith's (1965) "Series I" dunes. The Snake River, a tributary to the Niobrara River (Fig. 1), traverses the northwestern part of this dune belt and parallels the south-facing slip face of a barchanoid ridge that is at least 12 km long. Typical of many barchanoid ridges in this area, the surface of this dune has been extensively reworked into small parabolic dunes (Smith's (1965) "Series III" dunes), which are themselves highly reworked. It cannot be ascertained either from field observations or from aerial photograph interpretation whether the section examined is part of the older barchanoid ridge or a younger parabolic dune, but the latter is more likely. Organic-rich silts in the terrace alluvium that underlies the eolian sand were dated. The uppermost organic-rich bed dates the beginning of eolian activity to sometime after ~2700 ¹⁴C yr B.P. The presence of a bioturbated paleosol in the eolian sands indicates that there were two phases of eolian deposition. Ahlbrandt *et al.* (1983) report ages of 940 ± 55 ¹⁴C yr B.P. (no NaOH treatment) and 780 ± 60 ¹⁴C yr B.P. (NaOH treatment) for organic-rich alluvium that underlies eolian sand at a locality on the Snake River ~10 km west of our locality. Because the uppermost dated alluvium

at the new locality is a maximum-limiting age, the eolian sand here may also be only a few hundred years old.

Belts of linear dunes and much smaller (generally <0.5 km), northwest-trending parabolic dunes occur immediately north and south of the Middle Loup River in the central Sand Hills (Figs. 1 and 2). Some of these small linear and parabolic dunes occur on top of much larger east-west-trending barchanoid ridges and therefore postdate the larger dunes. It is not clear from geomorphic relations whether the parabolic dunes are younger, older, or about the same age as the longer linear dunes, but both dune types have weakly expressed A/AC/C soil profiles, suggesting broadly similar ages. The Natick locality, described earlier by Ahlbrandt *et al.* (1983), is a cutbank of the Middle Loup River on the nose of a northwest-trending compound parabolic dune (Fig. 3). The locality exposes eolian sand underlain by alluvium that contains several organic-rich beds. A new AMS ¹⁴C age for organic matter in the lowest alluvial unit substantiates eolian activity beginning sometime after ~2600 ¹⁴C yr B.P., in broad agreement with a previous age reported by Ahlbrandt *et al.* (1983).

Eolian Deposition in the Past 1000 yr

The central Nebraska Sand Hills area has many complex dunes, with parabolic or linear dunes being superimposed

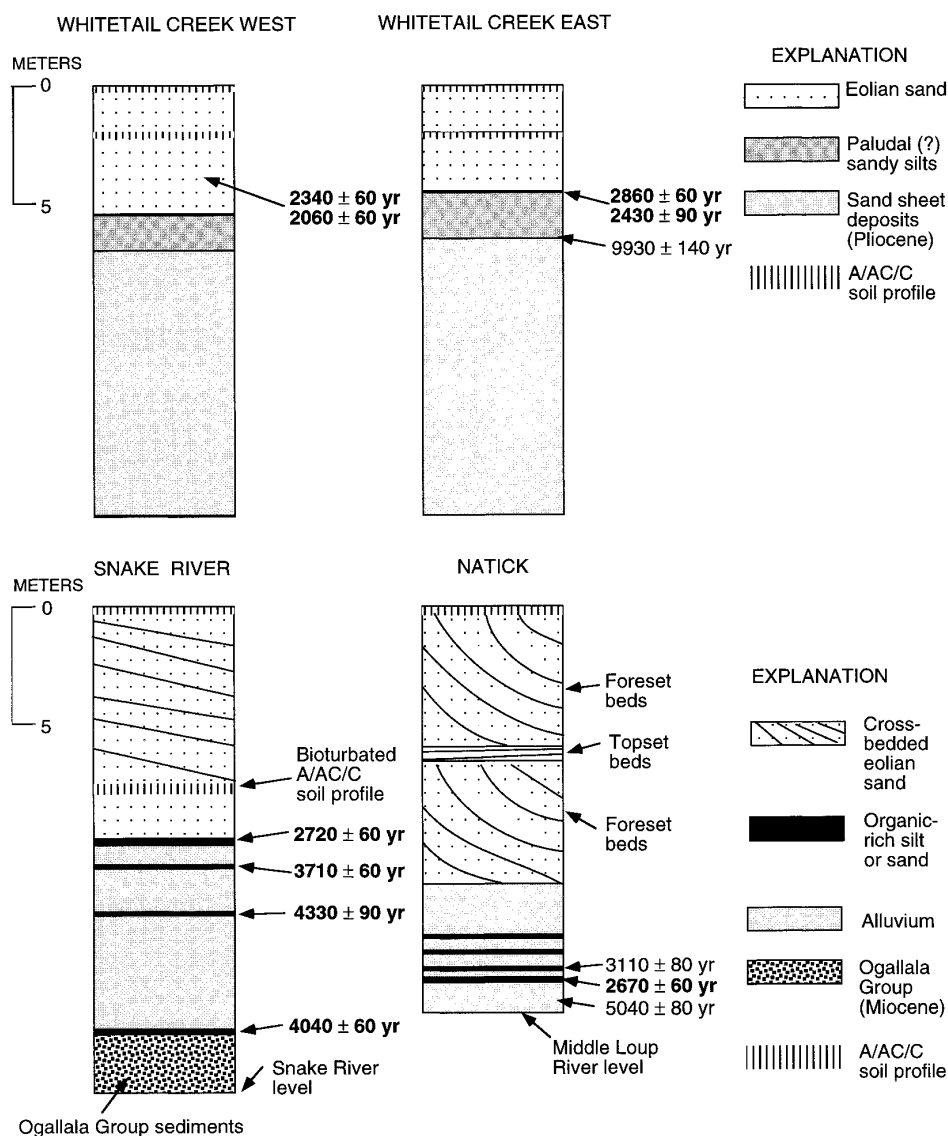


FIG. 3. Stratigraphy of eolian sand and underlying deposits and radiocarbon ages of bones and organic matter at the Whitetail Creek, Snake River, and Natick localities. Where pairs of numbers are shown, the top number is carboxyl radiocarbon age of bone and the bottom number is collagen radiocarbon age of same bone. Ages in bold numerals are those from this study; others are from Ahlbrandt *et al.* (1983).

on larger, older barchans. The youngest of these indicate eolian deposition in the past millennium. Near Seneca, Nebraska, we examined a series of exposures on the southeastern part of a dome-like dune that could be a highly modified barchan. The eolian sands near Seneca and in a quarry near Mullen ~12 km farther west have as many as three weakly developed paleosols with A/C/C profiles. Based on our new AMS ages of bison bone, there have been at least three, and possibly four cycles of eolian sand movement and soil formation during the past ~800 ^{14}C yr (Fig. 4). These ages are in accord with the conclusions of Stokes and Swinehart (1997), who report optically stimulated luminescence (OSL) ages for this locality.

Numerous smaller dune fields are found outside of the Nebraska Sand Hills in Nebraska and adjacent Colorado (Fig. 1). The largest of these sand bodies is the Wray dune field, which consists primarily of parabolic and compound parabolic dunes (Madole, 1995; Muhs *et al.*, 1996a). In the eastern part of the Wray dune field a 16-m-deep deflation hollow called the Hoover blowout (Madole, 1995) exposes ~8 m of eolian sand within the nose area of a northwest-trending compound parabolic dune (Fig. 4). The eolian sands contain two buried soils with A/C/C profiles and are underlain by pond or lacustrine sands, silts, and clays. From the radiocarbon ages reported by Madole (1995) and a new age on bone that we report here, we infer that eolian sedimenta-

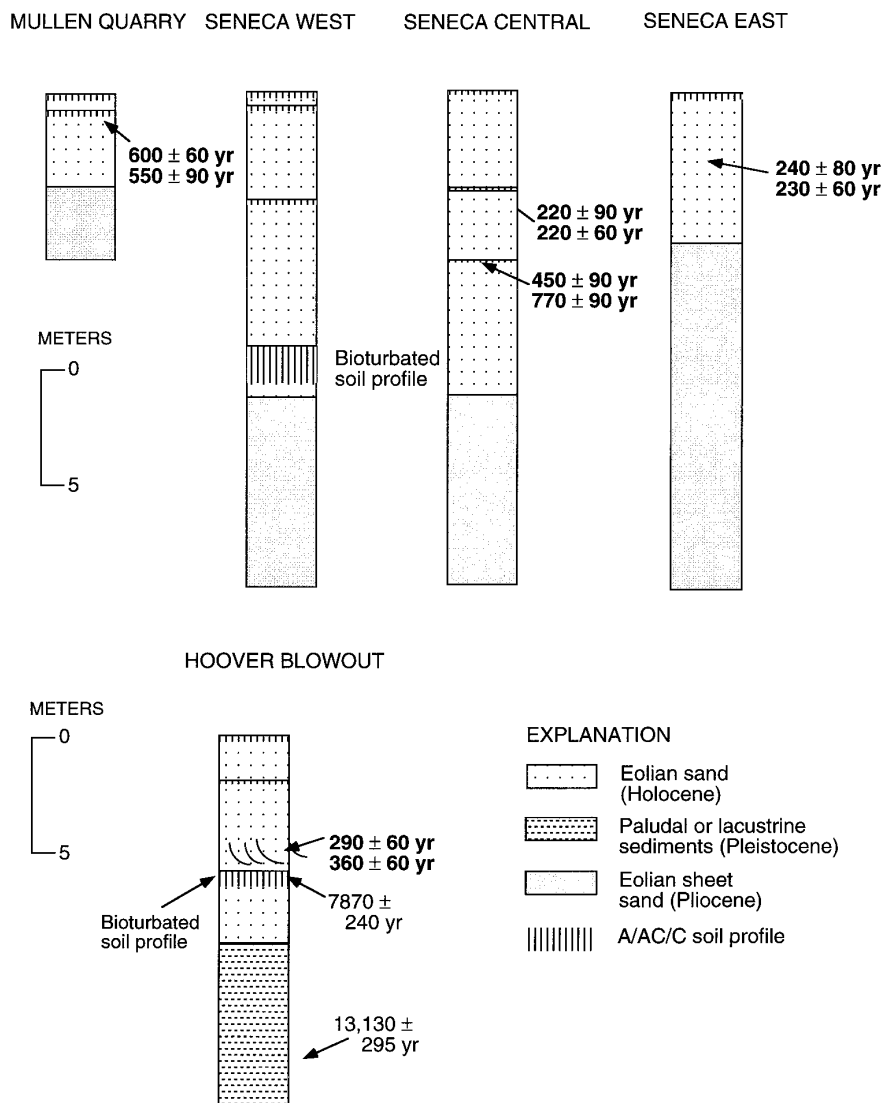


FIG. 4. Stratigraphy of eolian sand and underlying deposits at the Seneca, Mullen quarry, and Hoover blowout localities. Where pairs of numbers are shown, the top number is carboxyl radiocarbon age of bone and bottom number is collagen radiocarbon age of same bone. Single radiocarbon ages, not in bold text, at the Hoover blowout locality are from Madole (1995).

tion at this locality began sometime after $\sim 13,000$ ^{14}C yr B.P. and was episodic, based on the presence of the two buried soils (Fig. 4). The two most recent episodes of eolian sedimentation began sometime after ~ 7900 ^{14}C yr B.P. and apparently occurred within the past ~ 400 ^{14}C yr B.P. Thus, our new data indicate that the Wray dune field, like the Nebraska Sand Hills, has been active in the past millennium, consistent with the conclusions of Madole (1995).

Carbon Isotopes as Indicators of Nebraska Sand Hills Vegetation in the Past 3000 yr

The vegetation of the Nebraska Sand Hills about 1850 A.D., prior to major settlement, was Sand Hills prairie. This grassland assemblage contains elements of both tallgrass bluestem

prairie (*Andropogon–Panicum–Sorghastrum*), found to the east, and shortgrass prairie (*Bouteloua–Buchloe*), found to the west (Kuchler, 1964; Kaul, 1990). Mixed prairie (*Agropyron–Andropogon–Stipa*) is found to the northeast and southeast of the Sand Hills, but what Kaul (1990) refers to as Dakota prairie (*Agropyron–Stipa*) is found to the north of most of the dune field. Pollen studies at Swan Lake and Hackberry Lake (Fig. 1) indicate that prairie vegetation of some kind has been dominant over the southwestern Sand Hills since at least 9000 ^{14}C yr B.P. (Wright *et al.*, 1985) and over the northern Sand Hills since at least 5000 ^{14}C yr B.P. (Sears, 1961).

Carbon isotopic compositions of the dated bones are consistent with the grassland vegetation that has characterized the past few thousand years in the region. Two types of

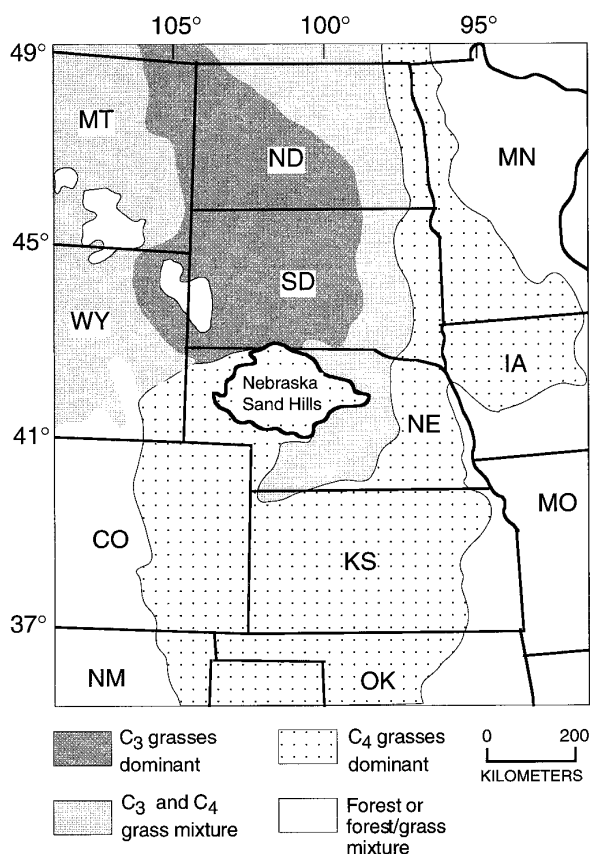


FIG. 5. Map showing distribution of grassland types (expressed as C_3 vs C_4 photosynthetic pathways) in the central and northern Great Plains (Kuchler, 1964; Kaul, 1990).

photosynthetic pathways, C_3 and C_4 , fractionate carbon isotopes in distinctly different ways. C_3 plants, which include both cool-summer grasses and all trees, have $\delta^{13}C$ values that range from about -22‰ to about -34‰ and average about -26‰ , whereas C_4 plants, which include most warm summer grasses, range from about -9‰ to about -20‰ and average about -12‰ (O'Leary, 1988). Teeri and Stowe (1976) found that the relative proportion of C_4 grasses in North America is positively correlated with summer temperatures and length of growing season. The northern Great Plains area is dominated by cool-summer C_3 grasses, and the central and southern Great Plains region, including the Nebraska Sand Hills, is dominated by warm-summer C_4 grasses (Fig. 5).

Experimental studies have shown that the $\delta^{13}C$ values of bone collagen reflect the carbon isotopic composition of plants in an animal's diet (Hare *et al.*, 1991). Therefore, $\delta^{13}C$ values of bison collagen can provide information on the relative proportions of C_3 and C_4 grasses that were in the grazing environment of the animals. The $\delta^{13}C$ values of bone collagen from Nebraska we studied range from -7.3 to -15.7‰ and are thus consistent with C_4 grasslands (Fig. 6;

Table 1). These values are similar to those reported by Madole (1995) for buried soil A horizons in eolian sand of late Holocene age in northeastern Colorado, and are distinct from those reported by David (1971a,b) for buried soil A horizons from the Brandon Sand Hills of Manitoba, where C_3 grasses are more abundant. Collectively, the data suggest that C_4 -dominated grasslands, similar to those of today, prevailed over much of the central Great Plains region of Nebraska and Colorado during the past ~ 3000 yr.

MINERALOGY AND GEOCHEMISTRY OF THE NEBRASKA SAND HILLS

We conducted mineralogical and geochemical studies of the Nebraska Sand Hills and made comparisons to dune fields in northeastern Colorado (Muhs *et al.*, 1996a), as well as possible source sediments, in order to assess the degree of mineralogical maturity of this sand sea. Mineralogical maturity in sandstones or sandy sediments derived from crystalline rocks is characterized by an abundance of quartz and depletion of feldspars (Blatt *et al.*, 1972). By this definition, many of the world's largest sand seas are mineralogically mature (Cooke and Warren, 1973; McKee, 1983; Pye and Tsoar, 1990). The degree of mineralogical maturity in the Nebraska Sand Hills is important because it has significance for the long-term evolution of the dune field.

Nebraska Sand Hills Compared to Colorado Dunes

Compared to dune fields in eastern Colorado, derived from South Platte River sediments, Nebraska dunes are enriched in quartz and depleted in K-feldspar, with approximately equal amounts of plagioclase (Fig. 7). Because X-ray diffraction is a semiquantitative technique, we also determined K_2O , Ba, and Rb concentrations in these samples. Barium and rubidium are trace elements that usually substitute for

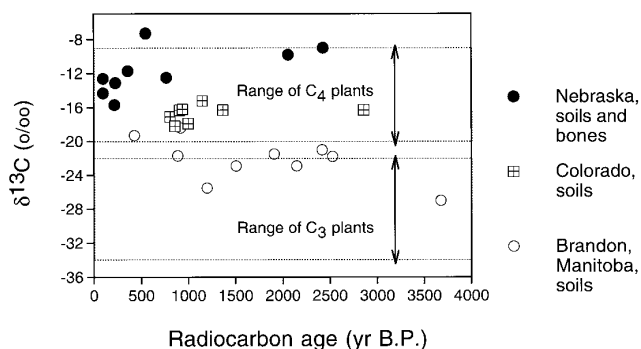


FIG. 6. Plot of $\delta^{13}C$ values in modern Sand Hills grasslands soils (data from Steuter *et al.*, 1990) and in bison bones from Nebraska (this study) as a function of AMS radiocarbon age. Shown for comparison are $\delta^{13}C$ values for buried soils in eolian sand in eastern Colorado (Madole, 1995) and southern Manitoba (David, 1971a,b) and ranges of $\delta^{13}C$ values for C_3 and C_4 plants (O'Leary, 1988).

TABLE 2
Analytical Data for Organic Matter-Rich Alluvium from Nebraska

LLNL no. ^a	INSTAAR no. ^b	Locality	Depth (m)	Fm ^c	Error	¹⁴ C age (yr B.P.)	Cal. age (2 σ) ^d (yr B.P.)
CAMS-11333	NSRL-1548	Snake River	9.5	0.7124	0.0047	2720 \pm 60	2945–2746
CAMS-11332	NSRL-1549	Snake River	10.65	0.6300	0.0046	3710 \pm 60	4232–3872
CAMS-11329	NSRL-1551	Snake River	12.5	0.5831	0.0061	4330 \pm 90	5254–4619
CAMS-11331	NSRL-1553	Snake River	17.3	0.6049	0.0041	4040 \pm 60	4813–4358
CAMS-11330	NSRL-1556	Natick		0.7169	0.0046	2670 \pm 60	2868–2726

^a Lawrence Livermore National Laboratory number.

^b Institute of Arctic and Alpine Research (University of Colorado) laboratory number.

^c Fm, fraction of modern ¹⁴C content.

^d Calendar age (calibrated from Stuiver and Pearson, 1993; Pearson and Stuiver, 1993).

K; thus, concentrations of all three elements are indicators of the relative abundance of K-bearing minerals. Geochemical results confirm the mineralogical analyses, as Colorado dune sands have K₂O, Ba, and Rb concentrations significantly greater than those of the Nebraska Sand Hills (Fig. 8).

Aerial gamma-ray surveys can be used to estimate the concentrations of K, U, and Th in soils. We generated a K concentration map from gamma-ray data in Phillips *et al.* (1993) with a calibrated grayscale and superimposed ground-based maps of the extent of dune sands in Nebraska and northeastern Colorado as an overlay (Fig. 9). This map shows that the Nebraska Sand Hills have lower K concentrations than dunes of northeastern Colorado or Tertiary bedrock sediment sources found to the west and northwest of the Sand Hills. The white tones for dunes in northeastern Colorado correspond to relatively high K₂O concentrations, in good agreement with XRF-based measurements. In contrast, the much darker tones in the Ne-

braska Sand Hills correspond to lower K₂O concentrations, with the lowest values in the western and north-central parts of the Sand Hills.

Analysis of eolian sands from deep drill cores indicates that K depletion is characteristic of more than just surface sands. Using a hollow-stem auger, we collected eolian sand samples near the crests of two east-west trending barchanoid ridges near Nenzel and the Gudmundsen Sandhills Laboratory (Fig. 1). The stratigraphy and a maximum-limiting radiocarbon age (at a depth of \sim 46 m) of \sim 13,000 yr B.P. for the Gudmundsen locality have been previously reported by Swinehart (1990). Results indicate K₂O concentrations very similar to those of surface samples in the Nebraska Sand Hills (Fig. 10) and indicate that deeper sediments are similarly K-depleted. We interpret these data, along with the uniformly low K₂O values in the surface sediments shown in Figure 8, to indicate that the dune sands of the Nebraska Sand Hills are not only K-depleted, but well mixed.

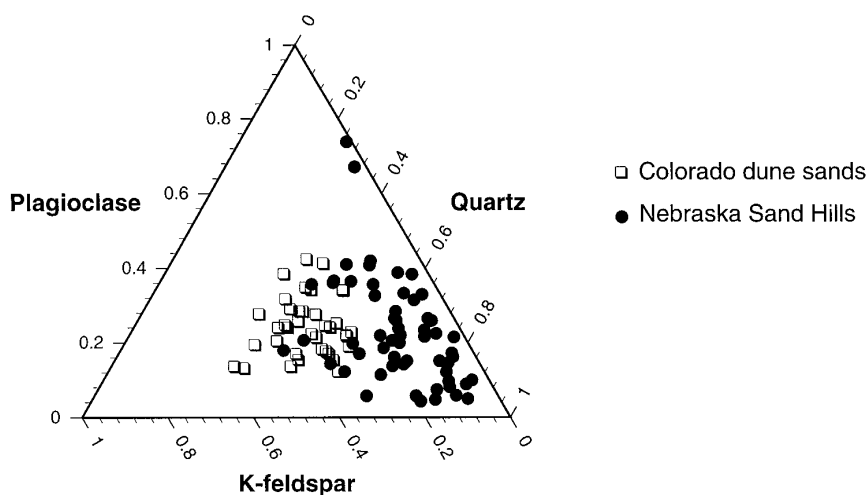


FIG. 7. Ternary plot showing relative abundances of quartz, plagioclase, and K-feldspar in the Nebraska Sand Hills compared to that seen in the Fort Morgan and Wray dune fields in Colorado.

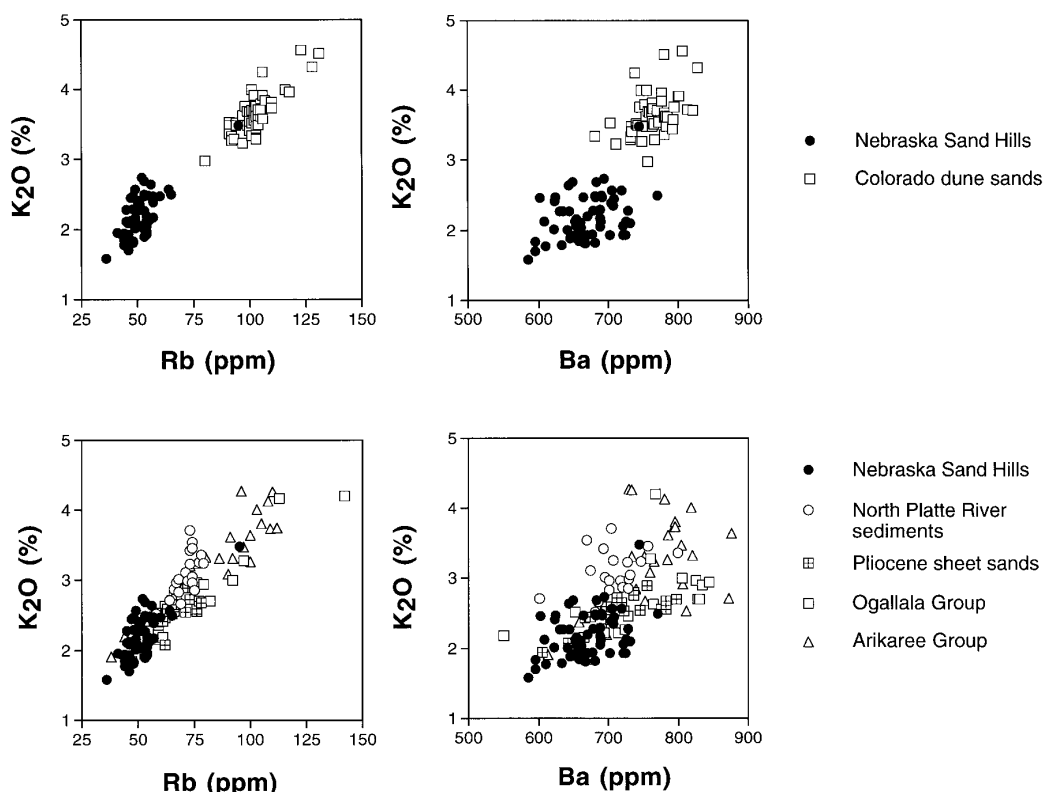


FIG. 8. Concentrations of K_2O , Rb, and Ba in the Nebraska Sand Hills compared to that seen in the Wray and Fort Morgan dune fields in Colorado and possible sediment sources in Nebraska. Colorado data from Muhs *et al.* (1996a).

Nebraska Sand Hills Compared to Source Sediments

We also analyzed the most likely sand-bearing source sediments surrounding the Nebraska Sand Hills, as well as dominant sand-moving winds. Tertiary bedrock of the Ogallala and Arikaree groups occurs northwest of the Nebraska Sand Hills and would be a potential source of sediments with northwesterly winds, such as those that occur during the fall, winter, and spring months (Fig. 11). These sediments could have also been reworked by streams during the Quaternary and then entrained by wind. The North Platte River is west and southwest of the Nebraska Sand Hills, and downstream from its confluence with the South Platte River, the Platte River flows to the southeast of the Sand Hills. During summer months, when a monsoonal flow of air from the Gulf of Mexico penetrates the region, southeasterly winds are strong enough to deflate sediment from the Platte River northwest into the Sand Hills (Fig. 11). Sediment from the Platte River would reflect both North Platte River and South Platte River sources, but we considered the North Platte River separately in our analysis, as the composition of South Platte River sediments is indistinguishable from that of Colorado dunes (Muhs *et al.*, 1996a). Another potential source is a predominantly eolian Pliocene sheet sand that underlies much of the Sand Hills (May *et al.*, 1995).

A comparison of Nebraska Sand Hills sands with these possible sediment sources adds further support to the conclusion that this dune field is mineralogically mature. Arikaree Group and Ogallala Group sediments have the largest range of K_2O concentrations, but most samples from these units have higher concentrations than those found in the Sand Hills (Fig. 8). North Platte River sediments have a smaller range of K_2O values, but most are also higher than those found in the Sand Hills. Pliocene sheet sands have K_2O concentrations that are not significantly different from the Sand Hills, but Rb concentrations that are mostly higher than the Sand Hills. Rb concentrations of all other sediment sources are generally higher than the Sand Hills, although Ba concentrations of all sediment groups show considerable variability. In summary, K_2O and Rb concentrations (and to a lesser extent Ba concentrations) in most candidate sediment sources for the Nebraska Sand Hills support the conclusion that these eolian sands are depleted in K-feldspar.

DISCUSSION

Late Holocene Radiocarbon Ages

The new AMS radiocarbon ages demonstrate that in three widely separated localities in Nebraska, eolian sand was

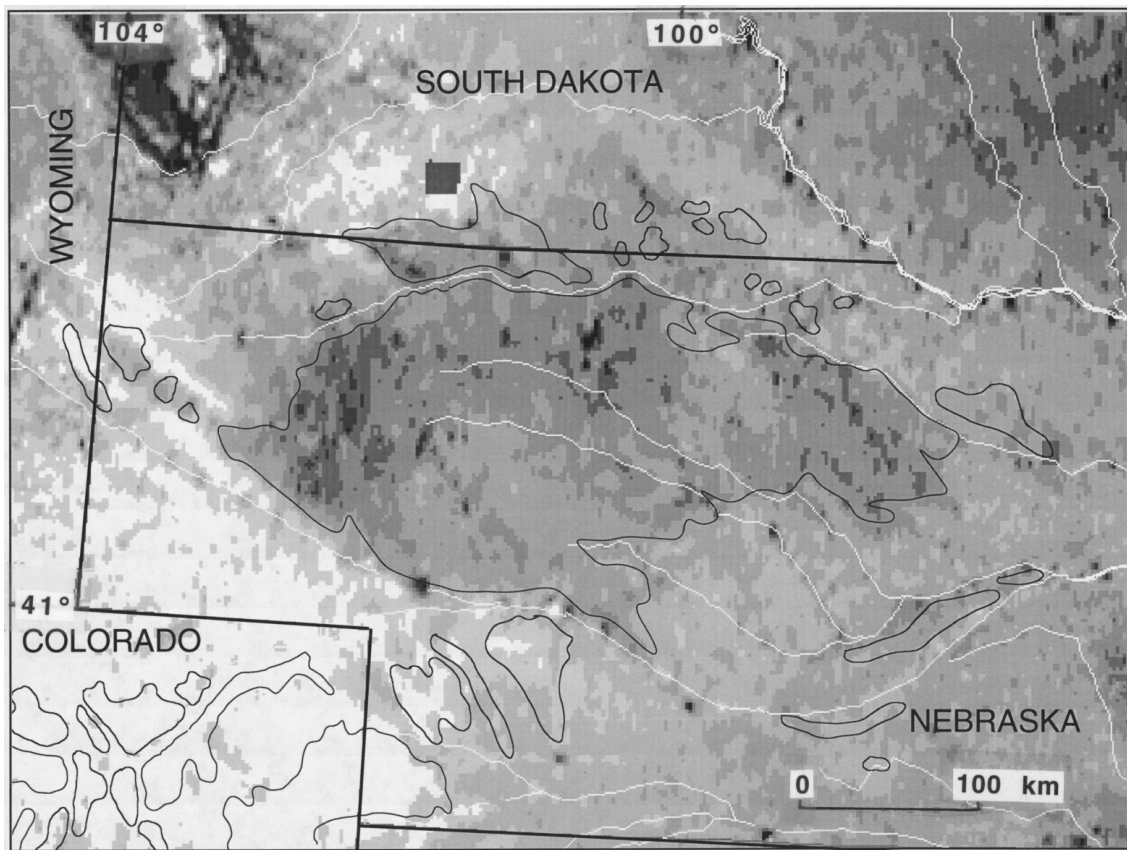


FIG. 9. Map showing relative concentrations of K in the Nebraska Sand Hills and surrounding areas derived from airborne gamma ray surveys. Lighter tones indicate higher concentrations of K; black lines outline dune fields. Generated from data in Phillips *et al.* (1993).

active in the past 3000 ^{14}C yr, and in three other localities, eolian sand was active in the past 800 ^{14}C yr. These conclusions are in agreement with new OSL ages reported by Stokes and Swinehart (1997). In addition, Muhs and Holliday (1995) presented historical evidence indicating that at least parts of the Nebraska Sand Hills may have been active during the late 1700s and 1850s A.D. Because modern winds are more than adequate for entraining sand (Fig. 11), the present stability of the Nebraska Sand Hills is due to the sparse vegetation cover. Therefore, past periods of eolian activity are indicative of severe droughts. A late Holocene record of salinity-sensitive diatoms from Moon Lake, North Dakota, shows that severe droughts (more intense than the 1930s "Dust Bowl" drought) occurred at least seven times in the past 2300 cal yr (Laird *et al.*, 1996). Stratigraphic and radiocarbon evidence for eolian activity after about 3000 ^{14}C yr B.P. from the Snake River, Natick, and Whitetail Creek localities may correlate with some of the major recorded droughts at Moon Lake in the past ~ 2300 cal yr.

Evidence from the Seneca, Mullen, and Hoover blowout localities indicates as many as three episodes of eolian sand movement in the past ~ 800 cal yr, and this corresponds to much of what is regarded as the Little Ice Age interval. In

the Rocky Mountains of Wyoming and Colorado, the Little Ice Age is well represented by the advance of glaciers that left the Gannett Peak and Arapaho Peak moraines, respectively (Davis, 1988). It is therefore important to know if drought conditions occurred on the Great Plains during the Little Ice Age. Because the Nebraska Sand Hills lie close to the C_4/C_3 grassland boundary (Fig. 5), which is temperature-sensitive, our carbon isotope data are an important test of the hypothesis of a colder Little Ice Age climate on the Great Plains. These data show no evidence of a greater abundance of C_3 grasses compared to the present (Fig. 6), indicating that temperatures were probably not significantly cooler than at present. In addition, both the Moon Lake diatom record and a diatom, ostracode, and bulk carbonate geochemistry record from Devils Lake, North Dakota, suggest several periods of aridity during the Little Ice Age on the Great Plains (Laird *et al.*, 1996; Fritz *et al.*, 1994). Tree-ring records from drought-sensitive red cedar and ponderosa pine in western Nebraska also show evidence of severe droughts in the past 800 cal yr (Weakly, 1962). Finally, a high-resolution sedimentary record from Elk Lake, Minnesota, shows periods of relatively high eolian sediment input during both the Little Ice Age and the period that preceded it (Dean *et al.*, 1994).

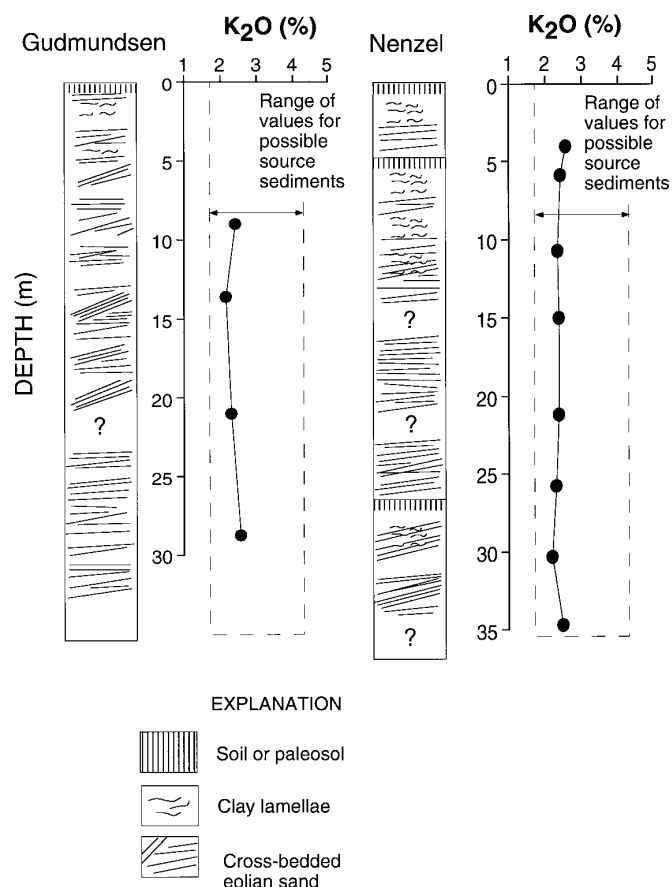


FIG. 10. Concentration of K_2O as a function of depth in two barchanoid-ridge dunes (locations in Fig. 1), compared to range of values in sediment sources (Fig. 8).

Thus, the combined eolian, lacustrine, and tree-ring records indicate that there were arid periods, with temperatures no cooler than at present, on the Great Plains during the Little Ice Age advance of glaciers in Wyoming and Colorado.

Significance of Weakly Developed Soils

An important conclusion from our dating is that very weakly developed A/AC/C soil profiles can form in less than a few hundred years (Figs. 3 and 4). Soils with morphologically distinct, clay-rich Bt horizons (other than clay lamellae; cf. Ahlbrandt and Fryberger, 1980), carbonate-rich Bk horizons, or even structural or color Bw horizons in eolian sand have not been reported by soil surveyors in the Nebraska Sand Hills (Kuzila, 1990). We examined hundreds of modern soil profiles in pits, blowouts, and roadcuts throughout the Sand Hills, and all have simple, weakly expressed A/AC/C profiles. Recent dating of eolian sands in Colorado indicates that Bw or Bt horizons probably take at least a few thousand years to form (Madole, 1995; Forman *et al.*, 1995; Muhs *et al.*, 1996a). Collectively, these observations imply that most

or all parts of the Nebraska Sand Hills were stabilized only 2000–3000 ^{14}C yr ago at the earliest, and probably more recently than that.

Cause of Mineralogical Maturity

Mineralogical maturity in a dune field that has been active in late Holocene time is a noteworthy phenomenon, and requires examination of possible causes. Several explanations have been offered for quartz dominance in sand seas. Some dune fields, such as the Algodones dunes of California, may be mineralogically mature because they are derived from source sediments that are themselves derived from old, multicyclic, mineralogically mature sedimentary rocks (Muhs *et al.*, 1995). Such a mechanism does not apply to the Nebraska Sand Hills, because our comparisons indicate that all possible source sediments are more K-feldspar rich than the eolian sands.

It is possible that K-feldspar depletion takes place in the Nebraska Sand Hills by chemical weathering when the dunes are stable. In this model, vegetation colonization stabilizes dunes and soil formation begins. Within the soil zone, chemical weathering by hydrolysis alters feldspars to clay minerals, with subsequent loss of K and other soluble elements. In a later phase of destabilization, feldspar-depleted sands from the soil zone are reworked into younger dunes. Repeated cycles of this process eventually lead to a feldspar-poor dune field. A problem with this process for the present Nebraska Sand Hills is that there is probably not much chemical weathering taking place in soils under prairie grass in a semiarid climate. On the other hand, chemical weathering could have taken place in the past if the Nebraska Sand Hills region supported a spruce forest, at least in valleys and interdune positions, as suggested by the pollen data of Watts and Wright (1966) and May *et al.* (1995). However, even under a spruce forest cover, it is not likely that chemical weathering can explain the observed K-feldspar depletion in the Nebraska Sand Hills. Colman (1982, and references therein), studying weathering rinds, established that K-feldspar shows little depletion due to chemical weathering in a wide variety of environments, including both coniferous forest and grassland, even after 100,000 yr. We conclude that chemical weathering does not explain K-feldspar depletion in the Sand Hills.

Wind abrasion can reduce sand-sized K-feldspars to silt sizes, with the result that silts are deflated away, leaving a quartz-sand-rich residue (Marsland and Woodruff, 1937; Kuenen, 1960; Greeley and Iversen, 1985). It is generally believed that sand grains in dune fields are well-rounded, and this roundness is interpreted to mean that wind abrasion is an important process in such environments. However, Goudie and Watson (1981) found that most sand grains in deserts around the world are subrounded to subangular. These data suggest that wind abrasion of grains is less important than is commonly assumed.

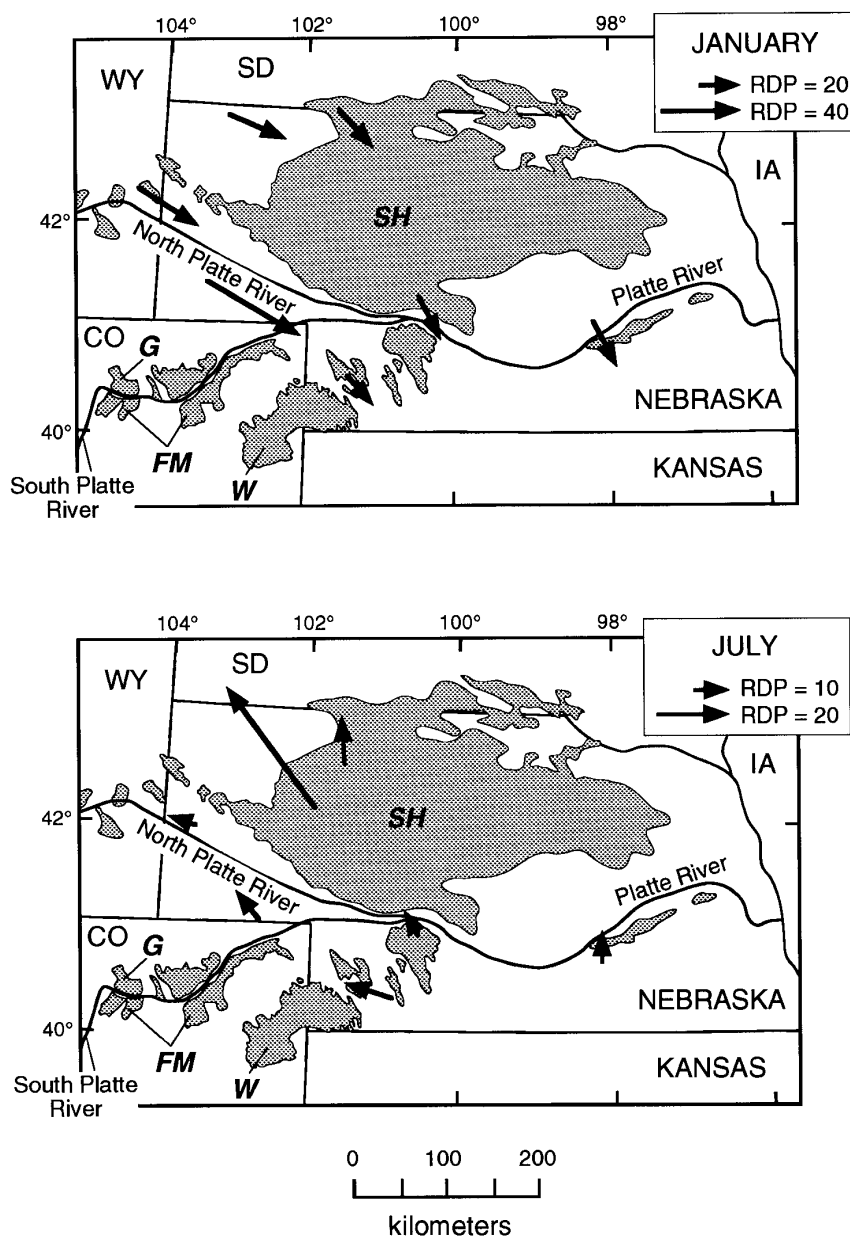


FIG. 11. Map showing resultant sand drift directions (shown by arrows) and resultant drift potentials (RDP) in vector units (shown by length of arrows) in Nebraska in January and July (terminology from Fryberger and Dean, 1979). SH, Nebraska Sand Hills; W, Wray dune field; FM, Fort Morgan dune field; G, Greeley dune field.

K-feldspar depletion may take place in the Nebraska Sand Hills while the dunes are active, but due to ballistic impacts rather than abrasion. Dutta *et al.* (1993) have shown on the basis of both theoretical calculations and laboratory experiments that ballistic impacts under strong (>10 m/sec) winds can result in the mechanical breakdown of K-feldspar to silt sizes. Silt-sized K-feldspars are then removed from the dune field by suspension in wind, leaving a quartz-rich dune field. A compilation of modern data indicates that winds in the vicinity of the Nebraska Sand Hills exceed the threshold velocity for sand movement (5 m/sec) about 40–60% of the

time and exceed the ballistic impact velocity (10 m/sec) 5–13% of the time. A comparison of particle size and sorting for the Nebraska Sand Hills (Ahlbrandt *et al.*, 1980) and Colorado dune fields (Muhs *et al.*, 1996a) indicates that Nebraska sands are in general finer grained and better sorted, which would be expected if ballistic impacts are the cause of K-feldspar depletion in Nebraska. In addition, it is expected that if silt-sized K-feldspar grains are transported out of the Nebraska Sand Hills in suspension, downwind loess deposits should be relatively enriched in K_2O , Rb, and Ba. The uppermost part of Peoria (late Wisconsin) loess was sampled, below

the zone of pedogenesis, from 45 localities downwind from the Nebraska Sand Hills in southern and southeastern Nebraska and northern Kansas in order to test this hypothesis. Results of bulk geochemical analyses indicate significantly higher K₂O, Rb, and Ba contents in loess compared to the Nebraska Sand Hills, which is also supported by the gamma-ray map of K concentrations (Fig. 9). However, while these data permit the ballistic impact hypothesis, they do not prove it. One important problem is that eolian sands tend to have low mica contents, because this platy mineral is not easily transported by saltation. In contrast, loess deposits tend to have fairly high mica contents. Therefore, part of the relatively high K₂O, Rb, and Ba contents in loess may simply be due to higher mica content rather than K-feldspar content. We emphasize that our data do not suggest that the Sand Hills are the primary source of loess in Nebraska. Although new thermoluminescence and radiocarbon ages show that there are both full-glacial and Holocene loesses in Nebraska (Maat and Johnson, 1996), many loess minerals, such as micas and carbonates, are absent in the Nebraska Sand Hills, which indicates distinctly different primary sources. Achievement of mineralogical maturity by ballistic impacts is likely to be a slow process. Therefore, the low K-feldspar content of the Nebraska Sand Hills suggests that these sediments have had a long history, with many episodes of activity spanning both glacial and interglacial climates, even though they have been most recently active in the late Holocene.

CONCLUSIONS

Stratigraphic and radiocarbon data indicate that eolian sand was active in the Nebraska Sand Hills in the past 3000 ¹⁴C yr in some localities and in the past 800 ¹⁴C yr in other localities. This eolian activity is due to droughts that were severe enough to remove the vegetation cover on dunes. Independent lacustrine and tree-ring records substantiate several droughts more severe than the 1930s Dust Bowl drought in the past two millennia, and it is likely that some of these were the primary cause of late Holocene eolian activity in the Nebraska Sand Hills. Carbon isotope data indicate that droughts were accompanied by temperatures similar to the present even during the Little Ice Age. Similarity of soils on dated late Holocene eolian sands with soils virtually everywhere else in the Nebraska Sand Hills yields the conclusion that this sand sea has everywhere been active at least once in the past few thousand years, though not necessarily at the same time. Despite this documentation that the Nebraska Sand Hills have been active very recently, mineralogical and geochemical data indicate that the dune field is mineralogically mature and well mixed, characterized by high quartz contents and depletion of K-feldspar. The most likely process that produced this mineralogy is ballistic impact reduction of K-feldspar, due to strong winds over

many cycles of eolian activity, probably during both glacial and interglacial periods. It is concluded, therefore, that the Nebraska Sand Hills have probably had a very long history. Based on the dual observations of recent activity and mineralogical maturity, indicating repeated cycles over a long time, the potential for reactivation of the Nebraska Sand Hills is high, with or without future greenhouse warming.

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